TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 754

AN INVESTIGATION OF THE PREVENTION OF ICE ON THE AIRPLANE WINDSHIELD

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SUMMARY

An investigation of three methods for the prevention and the removal of ice on an airplane windshield has been completed. The methods were: electric heating; hot-air heating; and an alcohol-dispensing, rotating wiper blade.

The results showed that vision through the airplane windshield could be maintained during severe icing conditions by the use of heat. When put in operation prior to the formation of ice on the windshield, the rotating wiper blade prevented the formation of ice. A combination of heated air and a rotating wiper blade would appear to protect against formation of ice on the windshield exterior, to prevent frost on the interior, and to provide for the removal of rainfall.

INTRODUCTION

The National Advisory Committee for Aeronautics is conducting a program of research intended to reduce the risks now attendant on airplane operation during icing conditions. A part of this program is concerned with the prevention of ice on the airplane windshield, which is a problem in urgent need of solution. An investigation of three possible solutions of the windshield icing problem has been completed. The methods investigated involve the use of: (1) heat from an electric source, (2) heat from the engine exhaust, and (3) an alcohol-dispensing, rotating wiper blade. Inasmuch as the problem of ice prevention exists in several forms, it is anticipated that several different methods may find application on the airplane. The obstructions of vision through a windshield may result from ice or snow formations on the exterior surface or from the formation of frost on the interior. The object of the present investigation, therefore, was to determine the extent to which the several methods could preserve vision. Observations were also made to determine the capacity of the rotating wiper blade to remove rain from the airplane windshield.

APPARATUS

Most of the tests of the various methods included in the investigation were made under simulated icing conditions in flight although some preliminary tests of the electrically heated model were made in the N.A.C.A. 7- by 3-foot ice tunnel.

In the flight tests, the temperatures necessary for icing conditions were obtained by climbing to the proper altitude. During the tunnel tests, the air temperature was controlled by a refrigeration system. Icing conditions were simulated during all the tests by establishing the necessary temperatures and discharging water drops from a spray nozzle into the air stream ahead of the models. The spray nozzle was located about 4 feet in front of the windshield test panel. The water-drop size, and therefore the type of ice, was controlled by the relation between the air pressure and the water pressure in the tube leading to the spray nozzle. In the determination of the capacity of the rotating wiper blades to remove rain, simulation of the natural condition of rainfall was also produced by the use of the spray nozzle.

Questions may be raised regarding the accuracy with which natural icing conditions were simulated by the means employed in these tests because of the lack of control over certain factors involved. Three such factors are the temperature and the velocity of the water drops at the time of impact and the humidity of the air. Although lack of control over these and other factors may introduce errors in the test data, the conclusions are believed to be free from important discrepancies because they are based upon the degree of ice protection during a controlled icing rate. The icing rate was made comparable with rates experienced during flight in natural icing conditions.

Electrically Heated Tunnel Model

The tunnel model of the electrically heated windshield was mounted in the leading edge of an airfoil shape as shown in figure 1. The dimensions of the transparent area of this model were 9 inches by 9 inches. The test panel was made of two panes of glass 1/8 inch thick mounted in a frame and separated by a 1/4-inch gap. The gap between the two panes of glass contained electric heating wires. A liquid dielectric, ethylene glycol, surrounded the heating wires to aid the transmission of heat from the wires to the glass and to prevent local overheating of the glass panes. Details of the construction of the panel rim provided for the electrical connections, the filling of the interior space with ethylene glycol and its retention, and a space into which the heated ethylene glycol could expand. The power was controlled by regulating the voltage across the heater with a rheostat.

Electrically Heated Flight Model

The flight model of the electrically heated windshield was mounted in the right front windshield frame of a four-place cabin monoplane (fig. 2). The dimensions of the transparent region of this panel were 5 by 9.75 inches. The outside dimensions of the frame, which was set into a cut-out in the regular windshield, were 8.1 by 13.1 inches. A photograph of the model prior to installation in the airplane is shown in figure 3(a). In addition to the heating-element wires between the panes of glass, a heating wire was enclosed within the rim of the panel. The width of the part of the rim exposed to the air stream was three-fourths inch. In other construction details, the flight-test model was similar to the one tested in the tunnel.

A section drawing of the flight-test model is shown in figure 3(b). The wiring diagram is shown in figure 3(c). The heating wires between the panes were spaced 0.56 inch. The power was supplied from two 12-volt batteries connected in parallel and controlled in a manner similar to that of the tunnel model.

Heated-Air Flight Model

The heated-air windshield model mounted for flight tests is shown in figure 4. The test panel, when mounted as shown, was set into the side window of the cabin airplane at an angle of 30° with the side of the airplane. This model had been mounted in a cut-out in the right front windshield during earlier tests. When thus mounted, the direction of the hot-air flow in the model with relation to the direction of the air stream over the outside was thought to be unfavorable to the most efficient operation of the heating system. In order to avoid the extensive changes required both to the airplane windshield frame and to the model to obtain a desirable orientation, the model was moved to the side location. The side mounting was therefore utilized for the rest of the tests because it eliminated the objectionable features of a mounting in the front panel of this particular airplane and yet provided conditions that would give valid test results. The dimensions of the exterior of the frame were 9 by 14 inches. The size of the transparent region over which ice was prevented was 6 by 11 inches. Some glass breakage was experienced during the early tests with this model owing to improper mounting of the glass. When the glass panes were uniformly heated and were protected from vibration or mechanical deflection, breakage did not occur.

The important details of the construction are shown in figure 5. The test model consisted of an intake duct, regulating check and bypass valves, frame, and two panes of glass. The glass panes were mounted in a frame and separated by a small air gap. Safety glass and double-strength window glass were used with equal success in the model. The structure of the frame provided for a variation of the gap between the panes of glass from three-sixteenths inch to one-eighth inch. This gap provided a duct through which heated air from the cabin air heater was passed.

The temperature drop of the air passing between the glass panes was measured by thermocouples located in the header and in the air outlet (fig. 5). The velocity of the air through the model was measured by pitot and static tubes located in the duct at the air outlet.

Rotating Windshield Wipers Tested in Flight

Tests were made of the rotating wiper blades in flight with the models mounted as shown in figures 6, 7, and 8. Three drives for the blades were used during the investigation. For the ice-prevention tests, an electric drive developed at the N.A.C.A. was used; the wiper blades were driven by a 50-watt electric motor through a flexible shaft at speeds varying from 300 to 750 rpm. In the rain-removal tests, two methods of driving the blade, a drive from the airplane engine through a tachometer shaft and a commercially developed 90-watt motor permitting wiper-blade rotational speeds up to 2,100 rpm, were used.

The wiper blades tested with the various drives are shown in figure 9. Each wiper blade covered a disk on the windshield 10 inches in diameter. Sections 9(a), 9(b), and 9(c) were developed at the N.A.C.A. laboratory. The wicks indicated in the figures were of wool felt. The wiper blades were constructed of 1/32-inch laminated rubber sheets. Sections (d) and (e) are adaptations of automobile windshield-wiper blades. Section (e) differs from section (d) only in that a shield is attached to the leading edge to aid in keeping the blade in contact with the glass when turning at high rotational speeds. Section (f), which has a solid rubber blade, was developed commercially for use on airplane windshields. Sections (a), (b), (c), and (f) have rigid frames running the full length of the blade diameter. Sections (d) and (e) are made of two 5-inch blades running from the hub outward. The blade sections are held in contact with the windshield glass by adjustable leaf springs mounted upon the blade hub center. Each of the rotating wiper-blade-shaft mountings provides for the discharge of a fluid, such as alcohol, from the center of the blade shaft upon the outside of the windshield. Isopropyl alcohol, 180 proof ethyl alcohol, and 180 proof ethyl alcohol with a denaturant were used with the wiper blade models during the tests.

TESTS AND RESULTS

Electrically Heated Tunnel Model

The results obtained in the ice tunnel from tests of the electrically heated windshield model are given in table I. The power required to prevent the formation of ice was measured during a test in which the panel was heated prior to discharging water drops from the spray nozzles. The model is shown in figure 10(a) after such a test had been made. When ice was allowed to form prior to heating the panel, removal was only partly effected, as is shown in figure 10(b). The attachment of the ice covering the heated area to that on bordering regions prevented the complete removal of the formation because only the ice in direct contact with the glass was melted. The bridging of ice from the unheated parts of the model apparently prevented the ice from coming in contact with the glass and therefore from being melted. The tunnel model failed structurally when a leak developed and permitted the ethylene glycol contained between the two panes of glass to escape. With no liquid surrounding the heating wires, the temperature rise of the glass near them caused the glass panels to break. Following the structural failure of the tunnel model, the tests were continued in flight on an improved test panel.

Electrically Heated Flight Model

The results of the flight tests with the electrically heated model are given in table II. Figure 11 shows the flight model after tests during which the formation of ice over the protected panel was prevented. The ice was kept from overhanging the protected region, as it had during the tunnel tests, by heating the rim of the protected area. The protrusion of the rim of the test panel about 1/16 inch from the surrounding windshield may also have aided in the prevention of the overhanging of ice from the unprotected areas. Vision through the double-glass panes and through the ethylene-glycol filler was satisfactory, being about the same as through a similar thickness of plate glass.

Heated-Air Flight Model

The data and the observations taken during the test with the heated-air model are recorded in table III. Tests were made during which ice was prevented from forming and in which a thin sheet of preformed ice was removed. Under icing conditions similar to those existent during the tests on other models, the heated-air panel gave satisfactory protection against the loss of vision. Although the use of the different gap sizes between the various panes of glass slightly changed the temperature distribution along the panel, the degree of ice protection was unaffected by this change. One flight was made to determine the manner in which and the temperature at which the hot-air method would fail to prevent ice. The temperature of the air was gradually reduced and the quantity of water discharged was increased to the largest amount that could be delivered to the spray nozzle. These conditions resulted in the formation of ice on the surrounding parts of the airplane windshield at the rate of about 1 inch in 3 minutes. After 20 minutes of flight with an air temperature of 8° F, about 75 percent of the area of the windshield remained clear. Ice was observed to form along the edges of the panel near the air-outlet end. The combination of air temperature and quantity of water used in this test is believed to represent an icing condition more severe than will normally be encountered by aircraft in flight. Unfortunately, photographic results of this test model could not be obtained owing to high air temperatures at the airport.

During the icing test with both the heated models, visibility through the test panel was poor because of the presence of unfrozen water drops on the exterior surface.

Rotating Windshield-Wiper Blades

Ice was prevented from forming by the rotating windshield-wiper blades but could not be removed if formation occurred before the blade was put in operation. Photographs showing the test panel after a flight during which ice was prevented from forming are shown in figure 12. All the alcohols used were satisfactory for the prevention of ice although the denatured alcohol, the contents of which are unknown, caused a slight blurring of vision through the protected disk. This difficulty was not encountered during the tests made with pure ethyl alcohol and with isopropyl alcohol. One gallon of alcohol was sufficient for a flight of 2 hours in moderately severe icing conditions. When ice was permitted to form prior to the rotation of the wiper-blade shaft, ice could not be removed. Attempts to operate the rotating wiper blade after ice had formed on the glass resulted in mechanical failure of the drive.

The blade design was controlled by the problem of removing rainfall rather than the prevention of ice. All the blades tested gave satisfactory ice prevention although only sections (a), (b), and (f) gave satisfactory removal of heavy rainfall. (See fig. 9.) Sections (d) and (e), although requiring less power than did the other model sections, were unsatisfactory because they were lifted off the glass by the air stream over a part of the swept area.

Ice was prevented on the windshield by shaft rotational speeds above 300 rpm. The removal of heavy rainfall required shaft rotational speeds in excess of 750 rpm. The 90-watt electric motor with which the commercially developed model was equipped seemed to be the minimum power with which a 10-inch-diameter blade could be driven.

DISCUSSION

The investigation of the prevention of ice on airplane windshields indicates that ice can be both prevented and removed by the use of electrically produced heat or heated air and can be prevented from forming by the use of a rotating wiper blade that dispenses alcohol from its center. The heated windshield will be most effective when it is heated before ice has formed on the glass.

The power required for the prevention of ice by the use of electrically heated wires at an air speed of 100 miles per hour was about 260 watts per square foot. About 2 watts of this power for each inch of rim of the protected panel should be concentrated in the frame to prevent ice from overhanging the edges. If the heated panel protrudes from the surrounding structure, the tendency of the ice to build out over the protected panel from the edges appears to be reduced. On the basis of observations made during the tests and of an analysis of the theoretical design of an electrically heated windshield, it is suggested that the heating wires be arranged perpendicular to the direction of the air stream. On the same basis, it is suggested that the wires be more closely spaced near the air-stream entering edge of the model than over the rest of the panel.

The heat required to prevent the formation of ice by the use of heated air at an air speed of 100 miles per hour was about 900 Btu per square foot per hour. Observations made during the test indicated the desirability of designing the air-heated windshield in such a manner that the flow of air between the panes of glass was in the same direction as the air passing over the exterior. The heat that enters the exterior boundary-layer air at the forward end of the model raises the temperature of the air that passes over the rest of the model and therefore reduces the total quantity of heat that is required to maintain the panel at a given temperature.

The use of the rotating wiper blade dispensing alcohol provides for the removal of rainfall as well as for the prevention of ice and therefore may be preferable for some airplanes to the other methods. The advantage of the rotating wiper blade seems to be that it is easily designed and easily adapted to existing aircraft. The wiper-blade method is, however, restricted because of its inability either to remove frost from the inside of the windshield or to remove a preformed ice sheet over the outside of the windshield. It is thought that provision for manual operation, such as by a handwheel, would overcome the second objection. Although the engine-driven wiper had such a provision, no observations have as yet been made on its operation. The method is further disqualified by the limitations in the area that can be covered by a rotating wiper blade and by a partial obstruction of the pilot's vision due to the location of the blade hub.

The heated-air panel appears to be the most satisfactory solution to the windshield-icing problem, provided that a source of air at a temperature of between 170° and 200° F is available. The heated-air panel has two advantages over the electrically heated panel: It is more easily designed and uses normally wasted exhaust-gas energy; whereas the electrically heated panel must be kept liquidtight and must use electric batteries for power. The heated-air model also has the same advantages over the windshield wiper with regard to the source of heat and, in addition, has the advantage of having no moving mechanical parts. A disadvantage of any system that makes use of heat alone lies in the inability of such a system to remove unfrozen water drops from the exterior windshield surface. Inasmuch as each of the systems tested has given, in some measure, satisfactory results, all systems are expected to find application according to the requirements and the limitations of the particular installation. Combining the rotating wiper blade with the hot-air system would give double protection against ice over a limited area. In addition, the interior of the heated windshield would be protected against frost and provision would have been made for some vision through the windshield when flying in rain. The existing practice of making the airplane windshield retractable or removable by the pilot may become unnecessary if adequate protection against loss of vision due to rain or ice can be provided. The possibility is therefore noted that the added design complications resulting from the installation of ice-prevention equipment may in part be offset by other design simplifications.

CONCLUSIONS

Tests in the 7- by 3-foot ice tunnel and in flight indicated that:

1. Ice could be prevented from forming on the windshield by electric heat, by heated air, or by an alcohol-dispensing, rotating wiper blade.

2. Preformed ice could be removed from the airplane windshield by the use of either electric or hot-air heating.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 14, 1939.

TABLE I. Results of Tunnel Tests of Removal and Prevention of Ice on Windshield by Electric Heating

[Heated area, 10 by 10 in.; transparent area, 9 by 9 in.]

Type of test	Air speed (mph)	Air temperature (°F)	Power required (watts per sq in)	Comments
Prevention	80	23	1.25	Ice prevented. (See fig. 10(a).) Formations at edge of test panel 1-1/4 inches thick. Vision clear. Ice showed some tendency to build out and over panel at the entering edge.
Removal	80	23	1.60	Ice removed from about 20 percent of panel in 15 minutes. (See fig. 10(b).) Ice melted beneath formation but web-like crust not removed except at top of panel.
Removal	80	25	1.89	Ice removed from 30 percent after 10 minutes. Loss of ethylene glycol due to leakage, 60 percent. No ice removed over that section not containing ethylene glycol. Tests discontinued because of failure of model.

TABLE II. Results of Flight Tests of Removal and Prevention of Ice on Windshield by Electric Heating

[Heated area of pane (transparent), 5 by 9.75 in.; total heated area, 8.1 by 13.1 in.; cabin temperature, 40° F.]

Type of test	Air speed (mph)	Air temperature (°F)	Power: Pane (watts per sq in)	Power: Rim (watts)	Altitude (ft)	Comments
Prevention	95	26	1.43	63	12,000	Ice prevented over 100 percent of test panel in continuous operation. Small preformed formations were also removed. Visibility clear.[a]
Removal	90	25	1.43	63	12,700	After 11 minutes, ice melted free from pane and was blown away from 80 percent of the test panel. Lower edge remained covered owing to insufficient power in lower rim heater. Slight blurring between wires of test panel. Visibility poor.
Removal	98	25	.55	250	14,800	After 8 minutes, ice formation over panel melted free and moved sidewise until contact was made with ice over adjacent area. Rim power greater than needed.
Prevention	120	26	1.43	63	12,000	Ice prevented over 100 percent of test panel.[a]

[a]The ice-forming conditions did not require a rim heater except at leading edge. Ice was removed from unprotected areas along sides and at top of heated panel, indicating that rim heaters along those edges were not required.

TABLE III. Data from Tests on Windshield Panel When Heated by Cabin Air Heater

[Transparent area, 6 by 11 in.; total area heated, 9 by 14 in.; approximate cabin air temperature, 60° F.]

Ambient air		Panel-heating air			Space between panes (in.)	Btu / (sq ft/hr)	Remarks
Velocity (mph)	Temperature (°F)	Velocity (fps)	Temperature In (°F)	Temperature Out (°F)			
[a]106	27	47	172	137	3/16	800	Ice prevented and removed.
[a]114	27	67	180	148	3/16	1,000	Do.
[b]91	30	67	168	147	1/8	430	Do.
[b]92	31	49	165	153	3/16	280	Dry air.
[b]92	31	49	160	147	3/16	320	Ice prevented and removed.
[b]119	8	--	170	--	3/16	--	Ice prevented over 75 percent of area.

[a]Runs made with panel in front windshield.

[b]Runs made with panel in frame on side of fuselage.

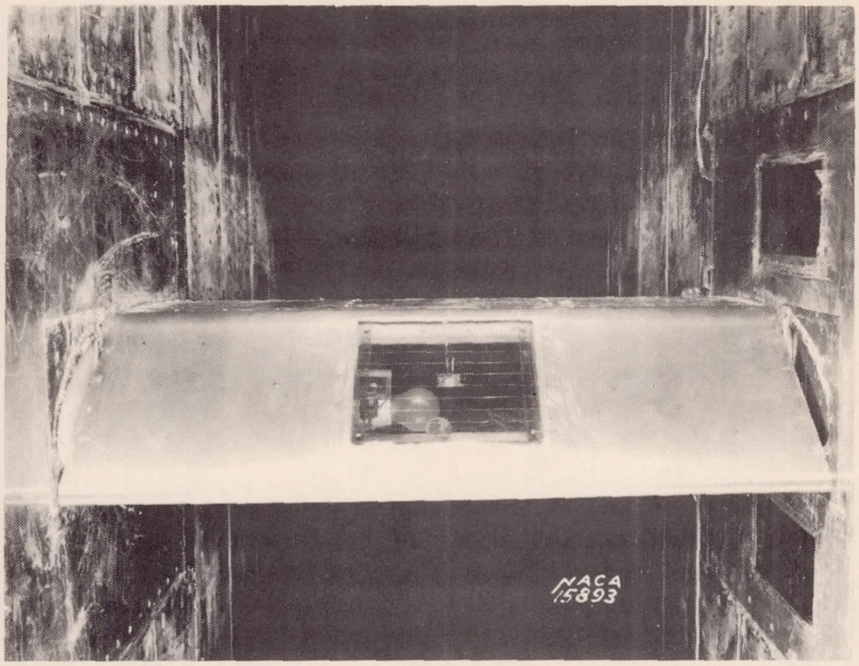


Figure 1.- Electrically heated windshield model mounted in N.A.C.A. ice tunnel.

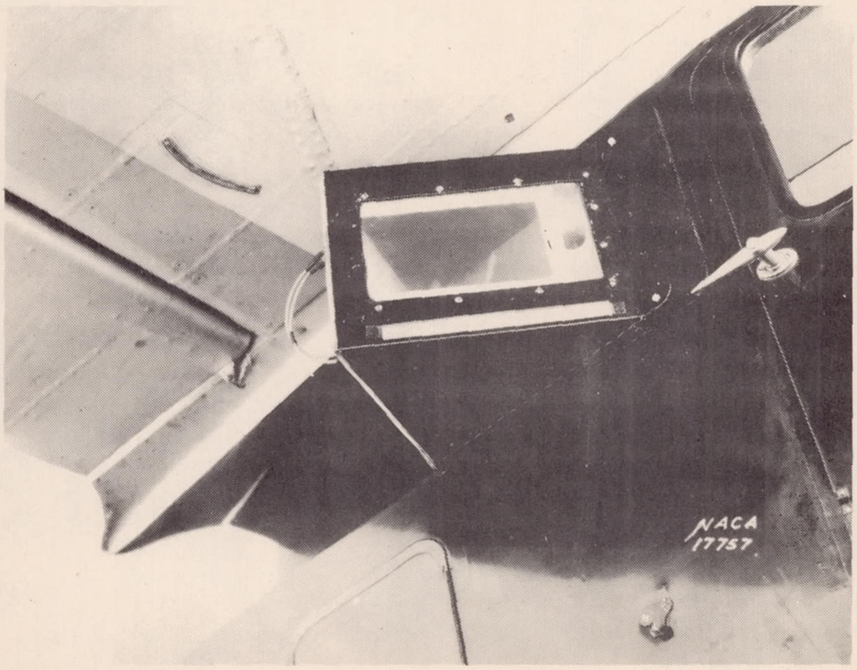


Figure 4.- Heated-air windshield model mounted in a frame at the side of the airplane fuselage.

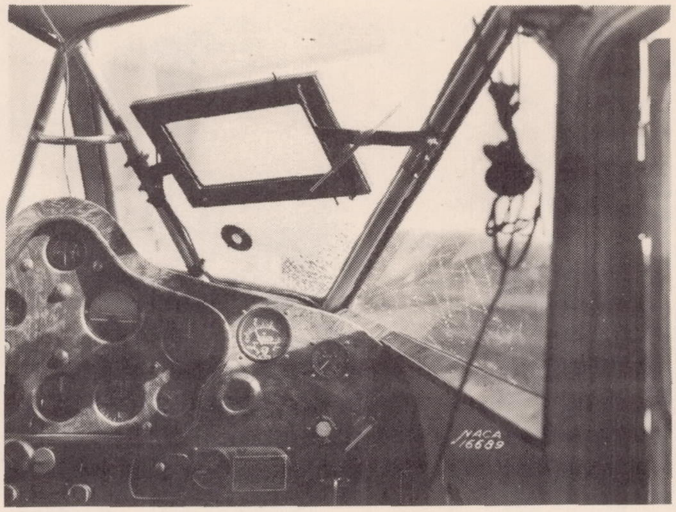


Figure 2.- Electrically heated windshield model mounted in an airplane windshield for flight tests. The main windshield is cut out to permit the insertion of the heated panel.

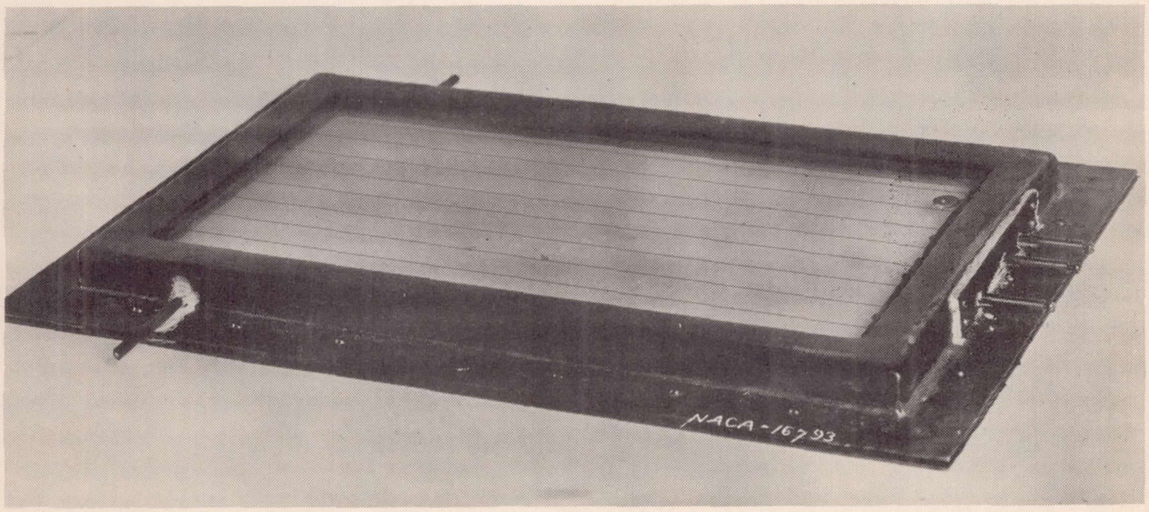
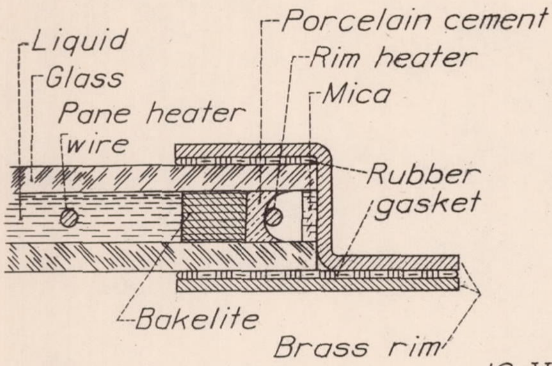
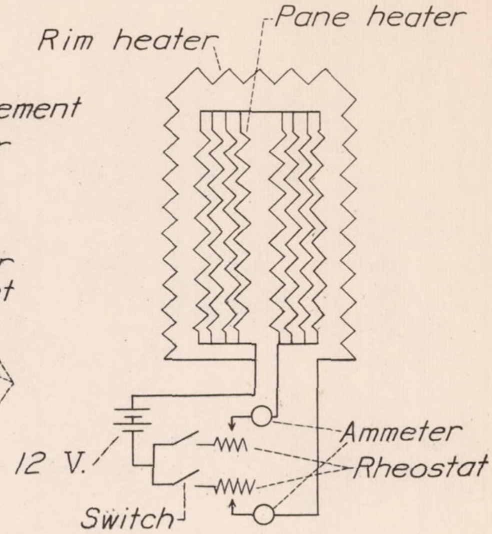


Figure 3(a).- Photograph of model.



(b)
Section through rim.



(c)
Wiring diagram of heating circuits.

Figure 3.- The electrically heated flight-test model.

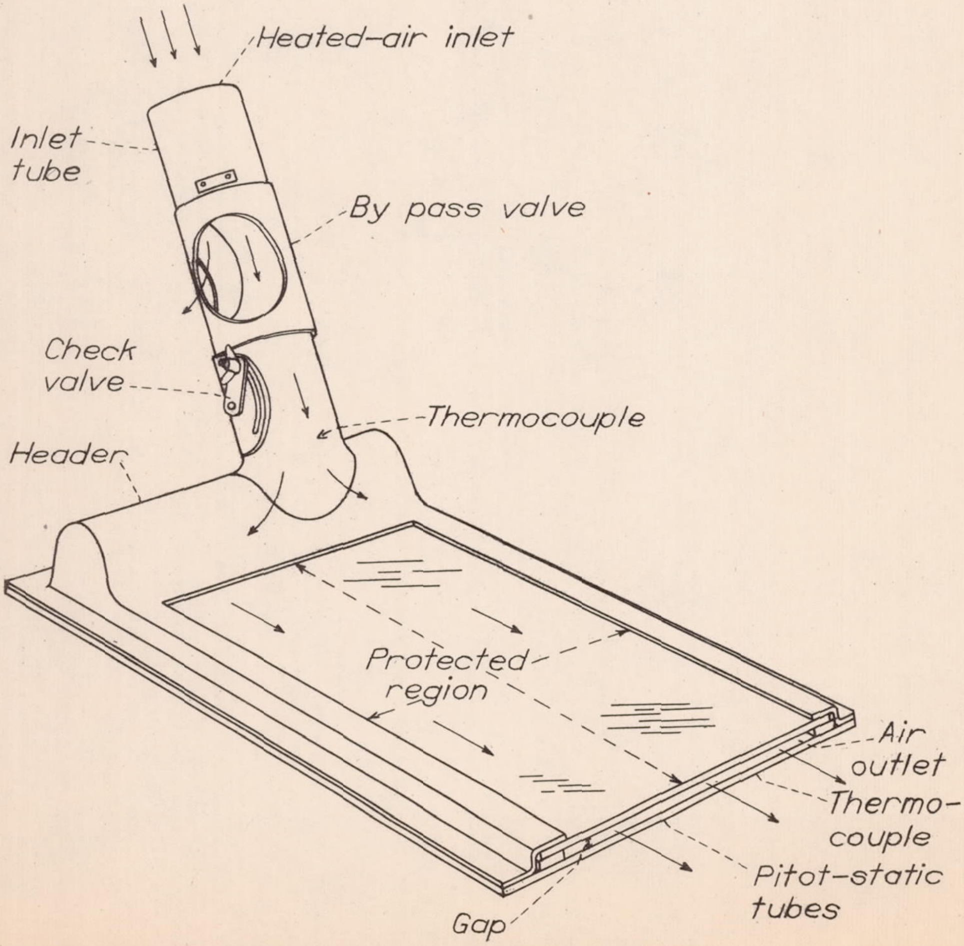


Figure 5.- The heated-air flight-test model.

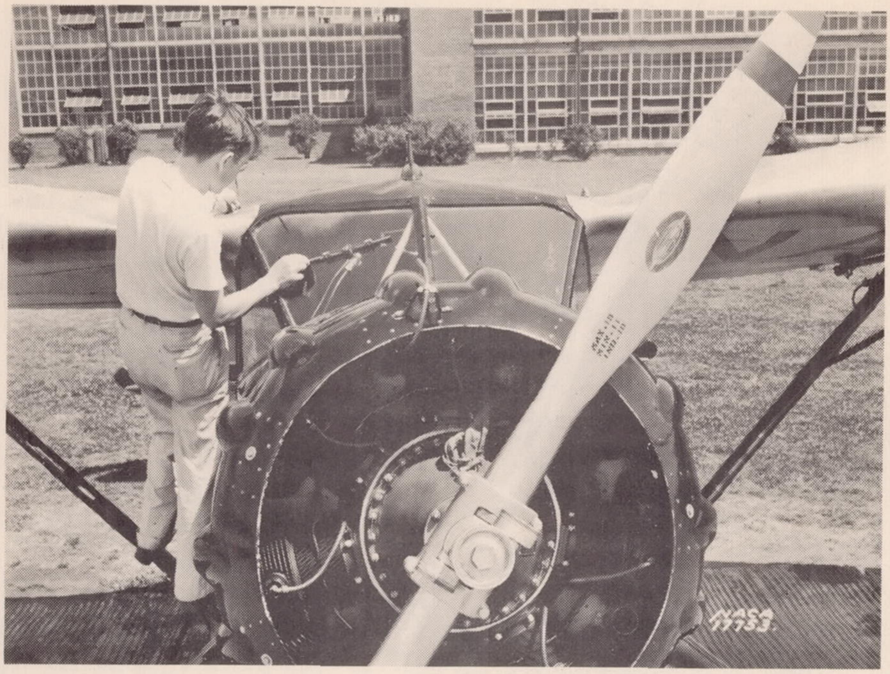
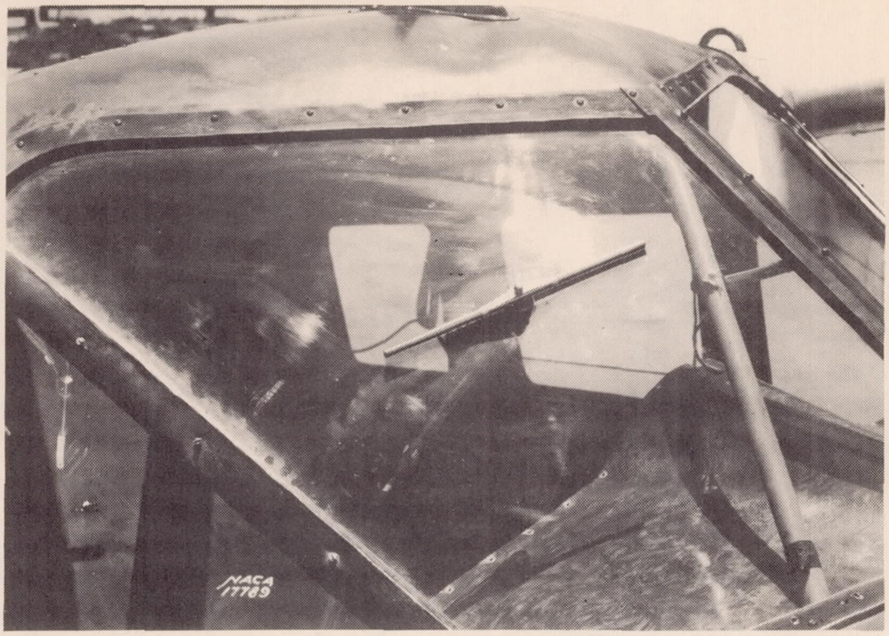
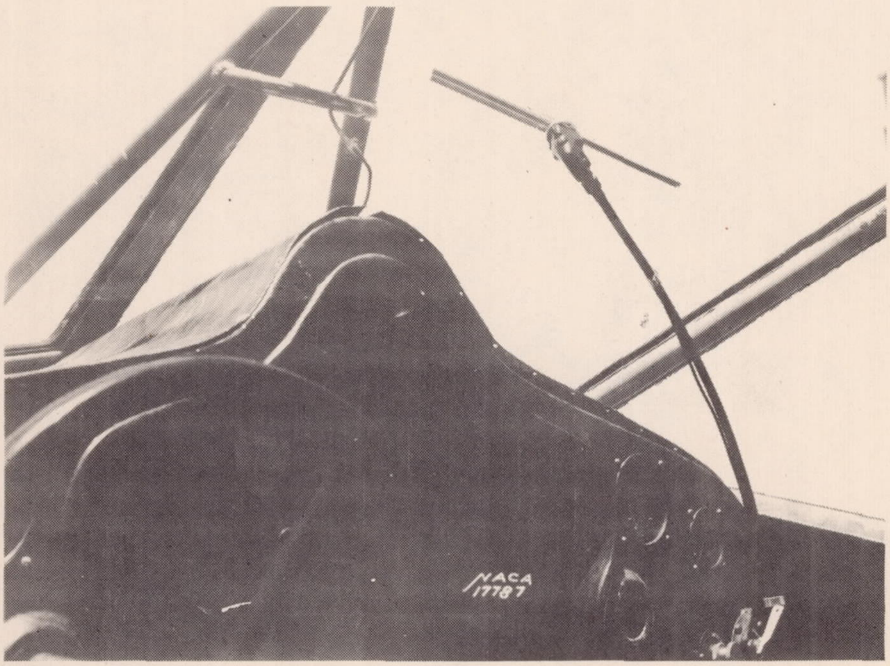


Figure 6.- Rotating wiper blade mounted in the windshield of a four-place cabin monoplane. The spray nozzle may be seen on the upper front of the engine cowling.

Figure 7.- An engine-driven rotating wiper blade, viewed from the interior of the airplane.



(a)



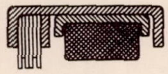
(b)

(a) View from the front of the airplane.

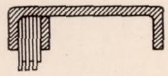
(b) View from interior of the airplane showing gear and shaft housing and, for a short distance along the shaft housing, a part of the alcohol tube.

Figure 8.- A commercial model of the electric motor-driven rotating wiper blade.

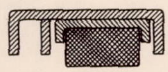
Direction of motion →



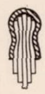
(a) N.A.C.A. wiper blade and wick.



(b) N.A.C.A. wiper blade only.



(c) N.A.C.A. wick only.

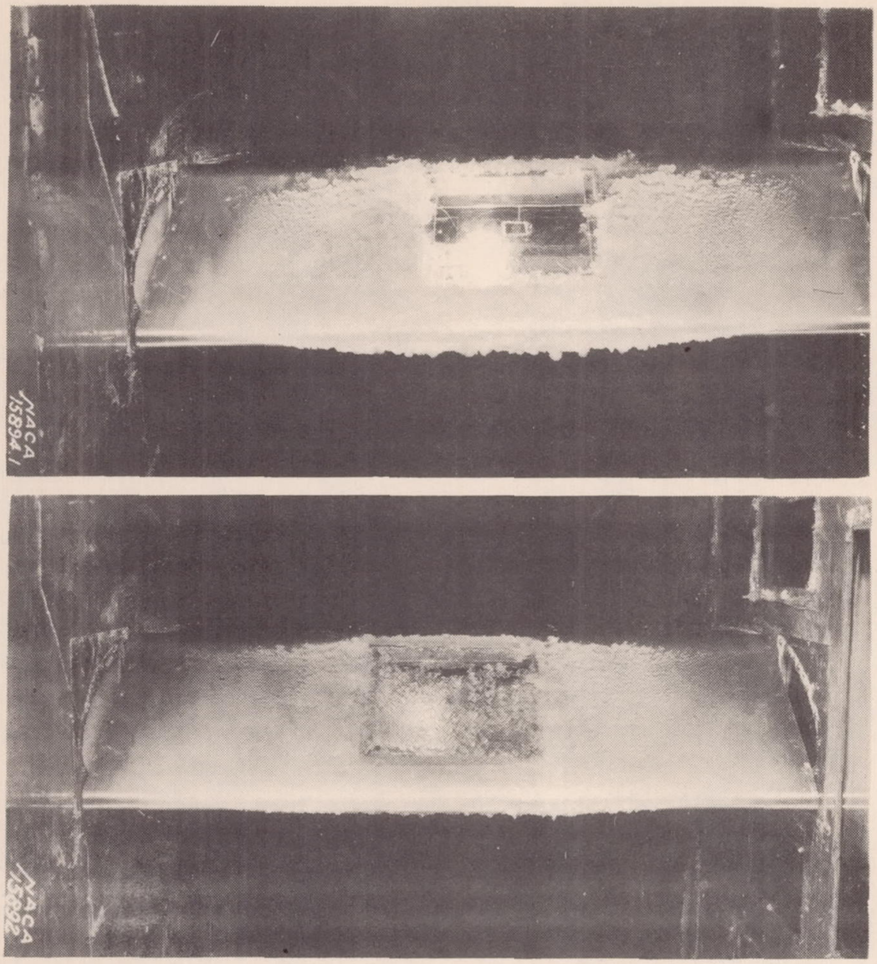


(d) Plain automobile wiper blade (blade in two sections).

(e) Automobile wiper blade with deflector (blade in two sections).

(f) Commercial design of airplane wiper blade.

Figure 9.- Section views of the blades used in ice-prevention and rain-removal investigations on the rotating-wiper-blade models.



(a) The model after an ice-prevention test.

(b) The model after an ice-removal test.

Figure 10.- Tunnel tests on an electrically heated windshield test panel.

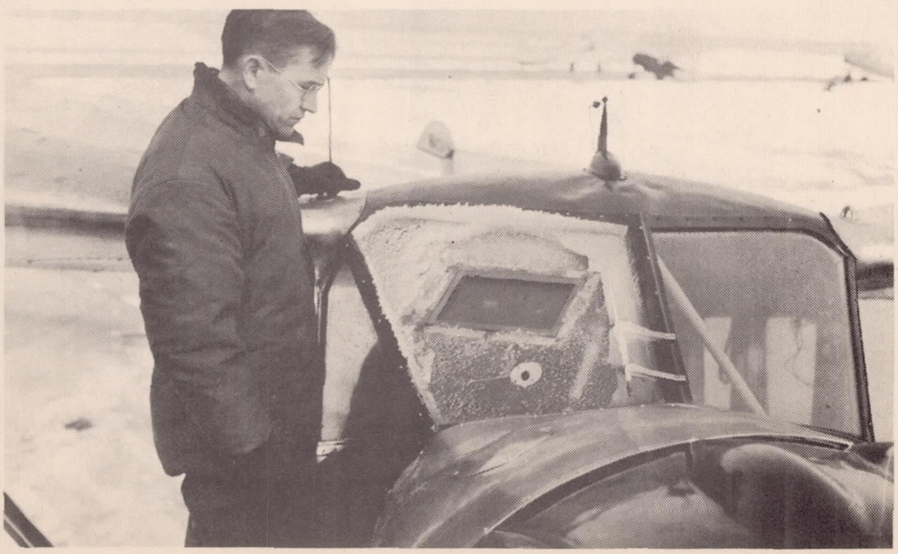
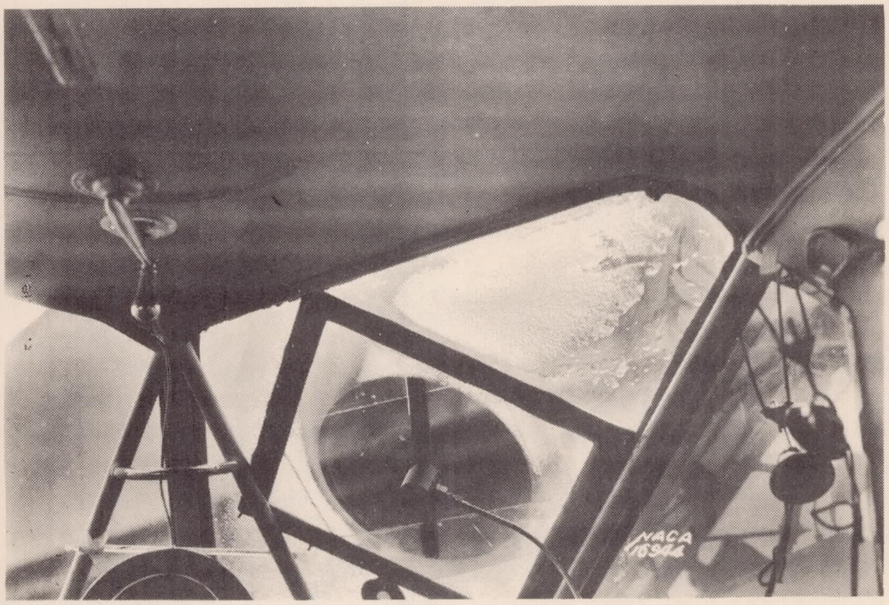


Figure 11.- The electrically heated flight test model after flights during which ice was both prevented and removed on the test panel. Note freedom from overhanging ice at the edges.

(a)



(b)

(a) View of the blade from in front of the airplane. Alcohol was discharged from the center of the blade onto the glass.

(b) View of the gear and shaft housing from the interior of the airplane. Alcohol was fed to the center of the blade through the gear and shaft housing.

Figure 12.- Electric motor-driven rotating wiper blade developed at the N.A.C.A.